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A Physical-Conceptual Model to Predict the Threshold Shear Velocity of Wet Sediment

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Introduction

A crucial parameter in predicting wind erosion is the threshold shear velocity. This is the minimal shear velocity required to initiate deflation of soil particles. Amongst the several factors that govern threshold conditions, surface moisture is one of the most significant. Through adhesion and capillary effects it strongly contributes to the binding forces keeping particles together (McKenna-Neuman and Nickling, 1989). Albeit the several studies that were conducted to determine the influence of moisture on entrainment of soil or sand particles by wind, its effect is still not well understood (Namikas and Sherman, 1995, Shao, 2000).

A new model to predict the threshold shear velocity for deflation of wet particles is presented in this paper. It is based on the balance of moments acting on wet particles at the instant of particle motion. The model includes a term for the aerodynamic forces, including the drag force, the lift force and the aerodynamic moment force, and a term for the interparticle forces. The effect of gravitation is incorporated in both terms. Rather then using an implicit function for the effect of the aerodynamic forces as in the model of Iversen and White (1982), a constant aerodynamic coefficient was introduced. The term for the interparticle force was deduced from consideration of the electrostatic force, the van der Waals force, and forces due to liquid-bridge bonding (capillary forces) and adsorbed-layer bonding (adhesion forces). The finally obtained model can be written as:

$$u_{*t} = \sqrt{A_1 \left[1 + w + A_2 \frac{1}{\left(\rho_s - \rho_f\right) g\, d^3} \left(d + A_3 \frac{\sigma^2}{\left|\psi_{md}\right| \mathrm{e}^{-6.5 \frac{w}{w_{1.5}}}} \right) \right]} \sqrt{\frac{\rho_s - \rho_f}{\rho_f} g\, d}$$

where u_{*t} is the threshold shear velocity (m s^{-1}), A_1, A_2 and A_3 are regression coefficients (resp. dimensionless, in N m^{-1}, and in kg^{-1} s^2), w is gravimetric moisture content (kg kg^{-1}), $w_{1.5}$ is gravimetric moisture content at –1.5 MPa (kg kg^{-1}), ρ_s is particle density (kg m^{-3}), ρ_f is fluid density (kg m^{-3}), g is gravitational acceleration (m s^{-2}), d is particle diameter (m), σ is surface tension (N m^{-1}), and ψ_{md} is matric potential at oven dryness (≈ -10^6 kPa). For detailed information about the model development, we refer here to Cornelis (2002).

Materials and Methods

The values for the parameters A_1 and A_2, were determined from non-linear least-squares analysis on the wind-tunnel data as reported by Iversen and White (1982) and validated on data from own wind-tunnel experiments on six fractions of dry dune sand and silt loam aggregates, with particle densities of resp. 2.65 Mg m^{-3} and 1.47 Mg m^{-3}. Note that the latter value corresponds to bulk density of the silt loam aggregates. The value for the parameter A_3 was derived from non-linear least-squares analysis on data from wind-tunnel experiments with the same but prewetted sediment, and the final model was validated against simulations with the model of Chepil (1956), which was, though controversial (Gregory and Darwish, 1990; Namikas and Sherman, 1995; Fécan et al., 1999), chosen for reasons as mentioned in Cornelis (2002).

The own experiments were performed in the closed-circuit blowing-type wind tunnel of the International Centre for Eremology, Ghent University, Belgium (Gabriels et al., 1997). The test section of the wind tunnel was 12 m long, 1.2 m wide and 2.5 m high, and the boundary layer was set at a height of about 0.60 m, by using a combination of spires and roughness elements (Cornelis, 2002).

A sample tray 0.95 m long, 0.40 m wide and 0.02 m deep was located at a distance of 6.0 m downwind from the entrance of the wind-tunnel test section. The tray was filled with air-dried or prewetted (by spraying a fine mist) sediment. The sample trays were then exposed to wind with different shear velocities and were subjected to evaporation in the case of the wet sediment.

A saltiphone, which is an acoustic sediment sensor that measures the number of saltating particles that bounce against a microphone (Spaan and van den Abeele, 1991), was continuously monitoring any particle deflating from the sample tray. It can hence be used to determine the instant of particle motion. The impact energy of the soil aggregates smaller then 200 μm was, however, too low to be recorded by the saltiphone. In those cases, particle entrainment was determined visually using a Neon-Helium laser beam (Logie, 1982).The detailed procedures to determine the deflation threshold for dry sediment and for wet sediment are both described in Cornelis (2002).

The wind velocity was measured at a 1-Hz frequency with 16-mm vane probes (Testo, Lenzkirch, Germany[1]) mounted at five different heights, and was used to compute the shear velocity using the well-known Prandt-von Kármán logarithmic law.

Moisture content was determined gravimetrically on three small samples taken down to 1 mm, from the instant of continuous particle entrainment, i.e. from the moment that three impacts were recorded on the saltiphone within one minute. Since we could visually observe differences in moisture content over the tray, two samples were taken at a dry section and one sample at a wetter section. Continuous deflation only occurred once the first dry sections appeared. The moisture content at –1.5 MPa $w_{1.5}$ was determined using a pressure chamber (Soilmoisture Equiment, Santa Barbara CA, USA).

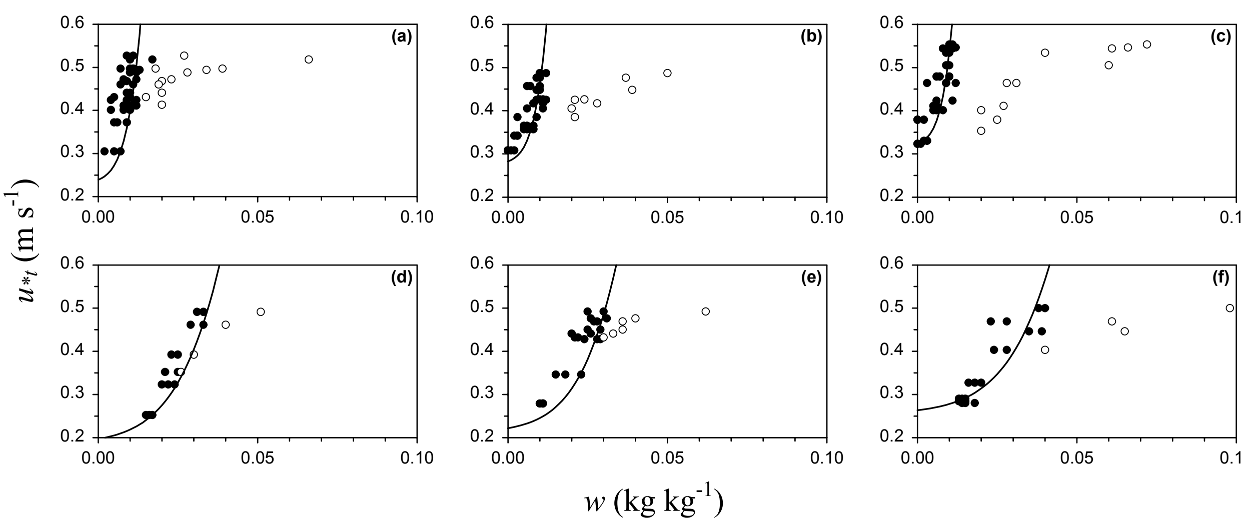
The relative humidity, evaporation rate and temperature were constant within each test run.

Results and Discussion

[1] Mention of company names is for the convenience of the reader and does not constitute any endorsement in whatever sense from the authors

The values for the parameters A_1 and A_2 as determined from non-linear least-squares analysis against the Iversen and White dry-sediment data (1982) were 0.013 and 1.7 10^{-4} N m^{-1} respectively. Our simple model (with $w = 0$) showed a similar performance with the model of Iversen and White (1982) and R^2 was resp. 0.997 and 0.992, when omitting the extremely high particle density data (8.9 Mg m^{-3} and 11.4 Mg m^{-3}). When validating our model against our own wind-tunnel data, R^2 was 0.995 and 0.972 for dune sand grains and silt loam aggregates resp.. This illustrates that it is acceptable to replace the implicit function in the Iversen and White model (1982) for the aerodynamic term with a constant, and that soil aggregates can be treated as individual particles with a density equal to their air-dry bulk density. Prediction of mass transport for a given soil should therefore be based on minimally-dispersed particle-size distributions, rather then fully-dispersed ones.

The third model parameter A_3, that expresses the effect of surface moisture, was determined from non-linear least-squares analysis against wind-tunnel experiments on prewetted sediment, and was found to be linearly proportional to d^2. In that respect, it can also be considered as a kind of compensation factor that keeps the term for the wet-bonding force scaled with u_{*t} which to a large extent depends on particle diameter d. In Fig. 1, the observed u_{*t} values are plotted as a function of w. Also plotted is the proposed model with $A_3 = 4\ 10^{14}$ d^2 kg^{-1} m^{-2} s^2. Although the data show a lot of scatter and R^2 was in all cases lower then 0.75, it can be seen that the model follows the dry-section data, where deflation was observed, rather well. At low moisture contents, the increase in u_{*t} with w is very gradual. But at a given moisture content, a steep increase in u_{*t} becomes apparent. The threshold shear velocity soon reaches a very high value and a critical moisture content, above which there is no wind erosion, can be observed. This is in line with observations of Chepil (1956), Bisal and Hsieh (1966) and Saleh and Fryrear (1995). Therefore, there is no need to quantify the upper boundary conditions of our model.



∗ observed (dry section)) observed (wet section) — calibrated model

Figure 1. Observed threshold shear velocity u_{*t} data vs. gravimetric moisture content w data for dune sand with particle-size range of 100-200 μm (a), 50-500 μm (b), 200-500 μm (c), and sand loam soil aggregates with particle-size range of 100-200 μm (d), 200-300 μm (e) and 300-500 μm (f). Also plotted is the presented model with $A_3 = 4\ 10^{14}$ d^2 kg^{-1} m^{-2} s^2.

As a validation, in Fig. 2, the threshold shear velocities u_{*t} as predicted with the model of Chepil (1956) is plotted against the threshold shear velocities u_{*t} as predicted with the model presented in this study. Figure 2 clearly illustrates that both models agree very well for threshold shear velocities not exceeding 0.5 m s^{-1}, which was about the maximum shear velocity generated in Chepil's study. This value corresponds with a $w/w_{1.5}$ ratio of 0.75 and is close to the critical moisture content above which no wind erosion will take place. This means that the soil surface has to dry to a rather low value before deflation will occur.

Conclusions

The presented model expresses the threshold shear velocity as a function of the soil-surface moisture content, particle diameter, and particle (or bulk) and fluid density. It is indexed to the moisture content at –1.5 MPa, a unique value for a given soil. Furthermore, it contains only three model coefficients. Although the model was derived from theoretical considerations it is rather simple. Calibration and validation of the model on dry and wet sediment showed that it performs very well.

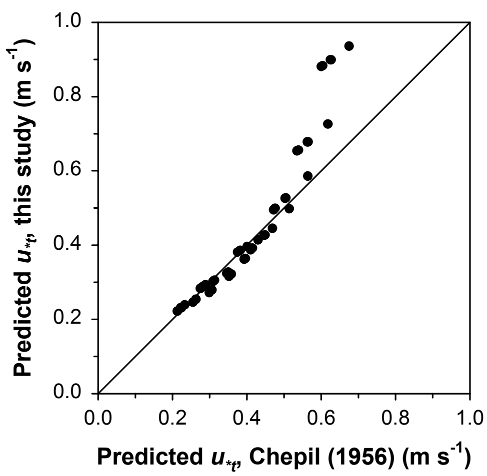


Figure 2. Threshold shear velocities u_{*t} as predicted with the model of Chepil (1956) vs. threshold shear velocities u_{*t} as predicted with the model presented in this study

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